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ABSTRACT

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The creation of closed ecological systems for supporting life during prolonged space flights is discussed. The main approaches toward studying energy efficiency and operational stability of such a system are examined.

The selection of animal and vegetable organisms which can exist /1*
within a wide range of external conditions is of paramount importance for creating closed ecological systems for supporting life during prolonged spaceflights and for establishing man on the moon and planets in the solar system.

Although a technical solution of the problem of man remaining outside of the earth for a prolonged period of time still entails many difficulties, it is nevertheless necessary at the present time to develop general theoretical approaches toward constructing an artificial cycle of matter and energy which can be maintained for a long period of time.

Under natural conditions, in nature stable biocenoses are characterized, as a rule, by the complex interaction of different types of

* Note: Numbers in the margin indicate pagination in the original foreign text.

population groups. Thus, not only populations belonging to different trophic levels interact with each other, but also populations located within one or another trophic level. Observations have shown that the complexity of ecological systems is accompanied in nature by an increase in resistance, due to an increase in the total volume of the system and to the possibility of forming different connections within the system when its environmental conditions are changed. It is apparent that the artificial closed ecological complexes, occupying limited space on the spacecrafts, will, to a considerable extent, not have these advantages which provide for the reliable operation of the system as a whole. In this connection, in the creation of a closed ecological complex, the study of the forms of interaction between components in the system, and the direction and stability of /2
the energy- and mass-exchange between elements of the ecological chain under normal and unfavorable conditions is of tremendous importance. These factors can in many ways determine the reliability of the exchange processes within the system as a whole, even when relatively unchanged properties of the individual elements in the ecological chain are retained.

Let us examine the main possible approaches to studying the problem of the energy efficiency and the operational stability of a complex system from the thermodynamic and kinetic point of view.

An artificial ecological complex can be regarded, on the whole, as a closed system, which consists of individual interconnected elements due to solar energy arriving from without. The entire energy- and mass-exchange within such a closed system can be represented as a consecutive and, generally speaking, branched chain for the transfer of matter and energy between the elements. Let our system consist of consecutive n elements (x_1, x_2 ... x_n), each of which can represent an individual component (including a component having a non-biological origin) in the ecological chain.

We shall employ the concepts of concentration or content below of certain elements or chemical compounds in the chain components, and the amount of free energy included in certain substances which are transmitted between the chain elements, with the corresponding transfer constants (or reaction constants) between the individual elements. These concepts (concentration, reaction constants) have in the given case a purely phenomenological meaning - i.e., they correspond to the content of a substance in the K^{th} component of the chain and describe the temporal nature of changes during the energy- and mass-exchange, but they in no way indicate the specific mechanisms taking place during these processes.

According to the thermodynamic representation of irreversible processes, the entropy production rate (energy dissipation) in an open system can be connected with the rates and energy decreases of the corresponding processes. The general condition for the energy-exchange of a closed ecological system can be expressed in the following form:

$$d_e S + d_i S = dS, \tag{1}$$

where d_eS is the entropy change of the external medium primarily due to the influx of free solar energy; d_iS is the entropy increase of the entire ecosystem due to the irreversible processes occurring within it; dS is the total entropy change (system + external medium).

In the stationary state $dS = 0$, and since $d_iS > 0$, then $d_eS < 0$. The term $d_eS < 0$ in equation (1) is connected with the increase of negative entropy due to the photosynthesis process in an element of the autotrophic photosynthesizing organisms, and the term $d_iS > 0$ is connected with an entropy increase in the energy-exchange processes /3 throughout all the elements of the ecological chain.

In the conjugation of energy dissipation and accumulation processes, it is necessary that

$$\frac{d_e S}{dt} + \frac{d_i S}{dt} = \frac{dS}{dt}, \tag{2}$$

while

$$\frac{d_i S}{dt} = \sum_{K=1}^{n} A_K j_K , \tag{3}$$

where A_K represents generalized forces which are proportional to the difference in the energy levels; j_K - streams (rates) of the corresponding energy- and mass-exchange process between adjacent x_K, x_{K+1} elements of the chain $x_1, x_2, .. x_n$. The difference of partial gas pressures for different components, the difference of chemical potentials, etc. can be of significance as a function of the specific conditions of A_K. In the stationary state, when $\frac{dS}{dt} = 0$, the rate at which negative entropy is produced in the photosynthesizing element under the influence of light must equal the rate at which free energy is exchanged in the ecological system. Otherwise the stationary state will not be achieved, and positive entropy can accumulate in the system which leads in the final analysis to degradation of the entire system.

Let us examine the term $\frac{d_i S}{dt} = \sum_{K=1}^{n} A_K j_K = P$, separately, which determines the rate at which energy is dissipated in the system:

$$x_1 \to x_2 \to \ldots x_K \to \ldots x_n .$$

It can be shown that for small energy drops between individual elements, when $\frac{A_K}{RT} \ll 1$, in the stationary state for

$$j_1 = j_2 = \ldots j_K = \ldots j_n = j \text{ stat.}$$

the quantity P assumes the smallest positive value which does not necessarily, however, equal zero:

$$P = \frac{d_i S}{dt} = \sum_{K=1}^{n} A_K j_K \geqslant 0. \tag{4}$$

By determining the experimental quantitities A_K, j_K, one can calculate the function P corresponding to a stationary state being established in the system. Methods such as this make it possible to study systems which are close to a thermodynamic equilibrium state for $\frac{A_K}{RT} \ll 1$, where the function P characterizes the stationary state. However, it is apparent that processes by which matter and energy are transferred in the ecosystems must take place far from a state of thermodynamic equilibrium, in view of the necessity of ensuring a significant exchange rate, and in view of the fact that components are included in the system which have significantly different energy levels. /4

In such situations, the following relationship can be employed:

$$\frac{d_A P}{dt} = \sum_{\kappa=1}^{n} j_\kappa \frac{dA_\kappa}{dt} \leqslant 0 , \tag{5}$$

while in a stationary state

$$\frac{d_A P}{dt} = 0 . \tag{6}$$

In particular, for a system of consecutive reversible reactions

$$x_1 \rightleftarrows x_2 \rightleftarrows \ . \ . \ . \ x_\kappa \rightleftarrows \ . \ . \ . \ x_n$$

the following function is applicable

$$\sum_{\kappa=1}^{n} r_\kappa j_\kappa^2 = j^2_{\text{stat.}} \sum_{\kappa=1}^{n} r_\kappa , \tag{7}$$

where r_K -, which depends only on the constant of the reaction rate - assumes a minimum value for

$$j_1 = j_2 = \ . \ . \ . \ j_\kappa = \ . \ . \ . \ j_n = j_{\text{stat.}}$$

in the stationary state which is distinct from the thermodynamic equilibrium state.

Thus, for a consecutive chain of energy- and mass-exchange, in many cases it is possible to find the functions determining the rate at which entropy is produced, or the energy dissipation functions per unit of time.

An experimental determination of the corresponding quantities in the equations (4, 5, 7) makes it possible to calculate these functions and to determine the region of the stationary state, its stability, and consequently the degree of reliability of the system. This type of approach can help, for example, in determining the most advantageous conjugation conditions, from the energy point of view, of the autotrophic and heterotrophic elements of the ecological system. It is apparent that the rate at which autotrophic organisms are photosynthesized must correspond to the rate at which oxygen and photosynthesis products are absorbed by the heterotrophic organisms. A determination of the rate at which free energy is produced and absorbed in these two processes is, in its turn, related to a study of the energy drops and rates during energy and matter exchange in a chain of intermediate compounds which participate primarily in the photosynthesis of respiration.

When studying ecological transfer chains, we can encounter difficulties of another type, however: the mathematical non-linearity of differential equations of energy- and mass-exchange. Let us /5
examine a system of differential equations for exchange in the chain:

$$x_1 \rightarrow x_2 \rightarrow \ldots\ x_{K-1} \xrightarrow{K_{K-1}} x_K \xrightarrow{K_K} x_{K+1} \xrightarrow{K_{K+1}} \ldots\ x_n$$

for any x_K component:

$$\frac{dx_K}{dt} = K_{K-1}\, x_{K-1}\, x_K - K_K\, x_K\, x_{K+1} \qquad (8)$$

$K = 1, 2, \ldots n.$

It can be seen that the terms determining the inflow ($K_{K-1}\ x_{K-1}\ x_K$) and the outflow ($-K_K\ x_K\ x_{K+1}$) for the component x_K depend both on the concentration of x_K and on the concentration of other elements in the chain: the donor (x_{K-1}) and the acceptor (x_{K+1}). This is natural, due to the necessity of close conjugation of the ecological chain components during the processes of energy- and mass-exchange. The dependence of terms in the right part of equation (8) on the product of the component concentration designates the non-linearity of transport differential equations, while this dependence is not definitely caused by the direct binary mechanism of exchange processes.

The unusual behavior of the system in time arises due to the non-linear nature of equation (8).

Thus, following the well-known example of Volterra regarding the interaction of two types of herbivores (A) and carnivores (B), these equations have the following form:

$$\left.\begin{aligned}\frac{dA}{dt} &= E_1A - AB \\ \frac{dB}{dt} &= AB - E_2B\end{aligned}\right\} \qquad (9)$$

Such a system can describe closed trajectories in the phase plane, which determines its stationary state. It can be seen that here in the stationary state $\frac{dA}{dt} \neq 0$, $\frac{dB}{dt} \neq 0$, which does not agree with the conditions of a stable stationary state for linear (in the mathematical sense) transfer processes.

In creating artificial ecological systems, we may encounter the necessity of constructing not only two-component systems (chlorella-human), but also systems consisting of three or more components having diverse qualities. In this connection, preliminary mathematical modeling of the energy-exchange processes is of great importance in studying the internal dynamic properties of such complex systems.

It is also of particular interest to study the role of different feedbacks in stabilizing the processes of internal energy-exchange.

A mathematical study shows that multi-component complex systems /6 having feedbacks which are described by non-linear differential equations are characterized by a very wide range of values included in the equation of parameters for which the systems remain stable.

A study of the energy- and mass-exchange processes in the molecular and sub-molecular levels in individual organisms is of great importance with respect to the problem of automatically controlling the state of individual components in the system. The necessity of this type of study is due to the possibility of directly employing the intermediate products of photosynthesis and respiration, and also to the necessity of utilizing different types of energy in cosmic space, besides light energy in the visible region of the spectrum.

As is known, in the photosynthesis process the absorption of a light quantum by pigments transfers an electron to the complex chain of consecutive oxidizing-reducing electron transmission events. An analysis of this process makes it possible to compare the transport equation for two adjacent terms in this consecutive chain (the cytochrom x_K, chlorophyll x_{K+1}):

$$\left.\begin{aligned} \frac{dx_K}{dt} &= K_{K-1}(a - x_K)^2 - K_K x_K x_{K+1} \\ \frac{dx_{K+1}}{dt} &= K_{K+1}(a - x_{K+1}) - K_K x_K x_{K+1} \end{aligned}\right\} \qquad (10)$$

The solution of this equation yields a stable point A on the plane (x_K, x_{K+1}). This means that the entire curve for the concentration change x_K, x_{K+1}, which passes in the vicinity of a particular stable point, strives assymptotically toward it. Thus, the concentrations x_K and x_{K+1} strive toward constant quantities, which designates that a stationary state has been established in the system. It is possible to determine the time required for the system to achieve a stationary state, which coincides with the experimental data. This type of study is of importance for automatically controlling the state of the photosynthesizing element under different conditions.

The examples presented above show that nonlinear systems with consecutive energy- and mass-exchange reactions can be characterized in several cases by a very unusual change in the component concentration in time. From the thermodynamic point of view, this must lead to corresponding changes in the entropy production (energy dissipation) by such systems.

For example, in the case of interaction between two types according to equation (9), a calculation of the function $\frac{d_A P}{dt}$ (5) leads to the following result:

$$\frac{d_A P}{dt} = (B - E_1) \frac{dA}{dt} + (E_2 - A) \frac{dB}{dt} < 0 \qquad (11)$$

It can be seen that the rate of change for entropy production per unit of time constantly changes when the total entropy increase is strictly positive. It is apparent that these facts must be taken into account during energy conjugation of this type of system with other components in the ecological chain, in order to assure their synchronous, joint operation. This material points to the fact that the energy state of a multi-component system is characterized by a complex and unusual interaction between individual components, in view of the dynamic properties inherent in each of them and in the entire complex system as a whole.

At the present time there are still no general methods for studying the behavior of a complex set of energy- and mass-exchange processes, their effectiveness, and stability.

There is no doubt that future development of these methods, employing the mathematical modeling of processes occurring in complex ecological complexes, will be of great importance for creating life-support systems on spacecrafts.

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